Revisiting of the greenhouse effect discovery and its analysis

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Outline

1. A short history of the greenhouse effect discovery

2. Analysis of the greenhouse effect using the Net Exchange Formalism

Emergence of the physics of climate

J. Fourrier:

• *Mémoire sur les températures du globe terrestre et des espaces planétaires,* Mémoires de l'Académie des Sciences de l'Institut de France,1824

• *General remarks on the Temperature of the Terrestrial Globe and the Planetary Spaces;* American Journal of Science, Vol. 32, N°1, 1837.

Joseph Fourrier
(1768-1830)

➢ He consider the Earth like any other planet

➢The energy balance equation drives the temperature of all the planets

➢ The major heat transfers are

1. Solar radiation
2. Infra-red radiation
3. Diffusion with the interior of Earth

➢The heat exchange with the interior of Earth has a negligible impact on the surface temperature

[Dufresne, 2006]

Emergence of the physics of climate

- He highlight the importance of solar and infrared radiation and makes an analogy between heat exchanges in the atmosphere and in a « hot box » (a greenhouse)

- He assume that the polar ward heat transport is small and deduced that, during the polar winter night, the polar temperature is equal to the temperature of the « *planetary space* »

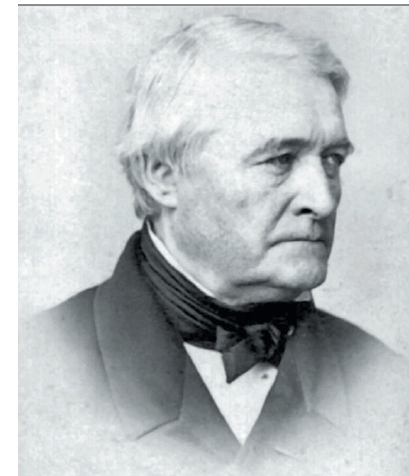
- He envisage the importance of any change of the sun « *The least variation in the distance of that body[the sun] from the earth would occasion very considerable changes of temperature.* »

- He envisage that climate may change: « *The establishment and progress of human society, and the action of natural powers, may, in extensive regions, produce remarkable changes in the state of the surface, the distribution of waters, and the great movements of the air. Such effects, in the course of some centuries, must produce variations in the mean temperature for such places* ».

Estimate of the solar irradiance

Mémoire sur la chaleur solaire, sur les pouvoirs rayonnants et absorbants de l'air atmosphérique, et sur la température de l'espace, Pouillet, 1838

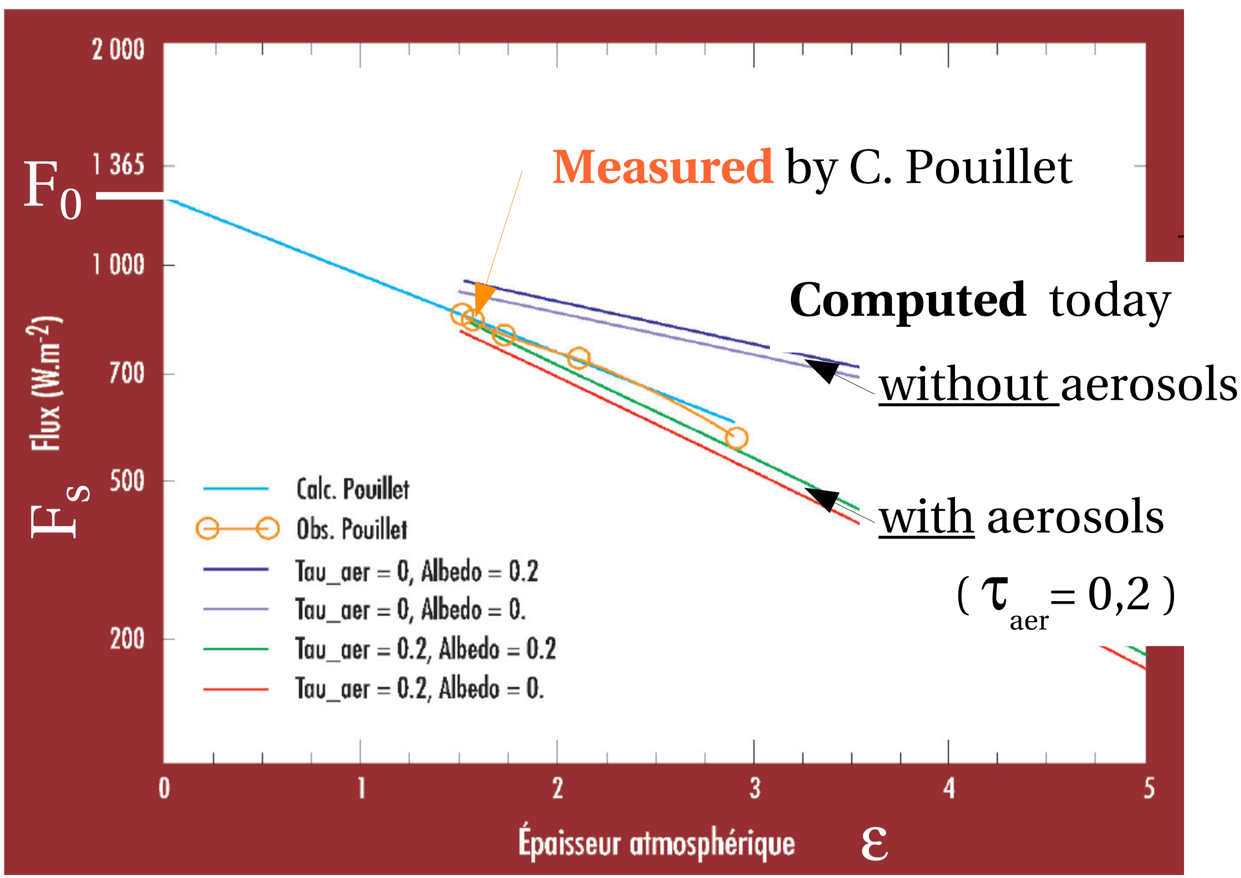
- Developed a pyrheliometer to measure the solar irradiance



Claude Pouillet

(1790-1868)

Solar irradiance at surface F_s as a function of atmospheric air mass ε



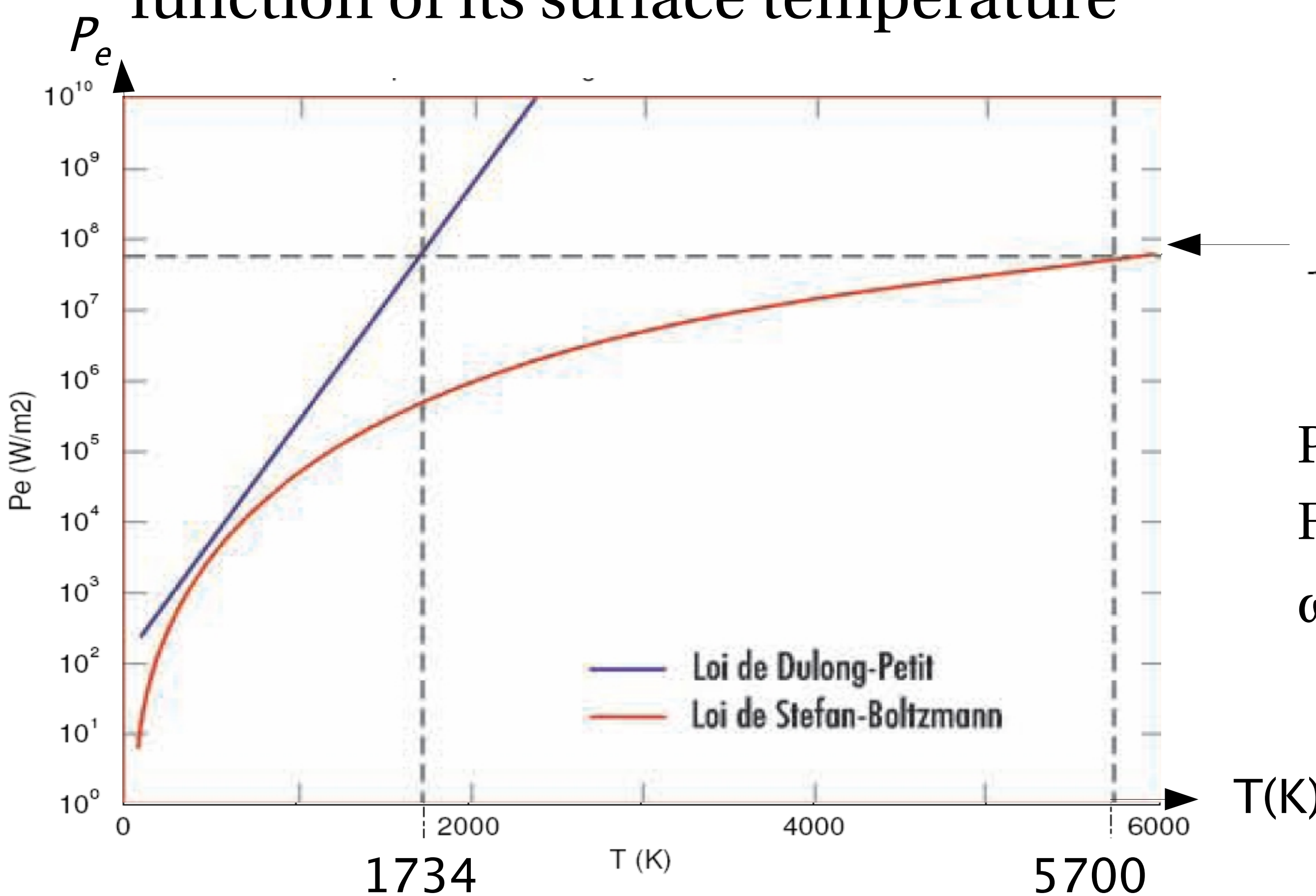
C. Pouillet obtains:
$F_0 = 1228\ W.m^{-2}$

Current estimate:
$F_0 = 1361\ W.m^{-2}$

[Dufresne, 2008]

… and of the surface temperature of the sun

Flux emitted by the sun as a function of its surface temperature



Pouillet estimate

$$P_e = \frac{F_0}{\sin^2 \omega}$$

P_e: flux emitted by the sun

F_0: solar constant

ω : angular radius of the sun

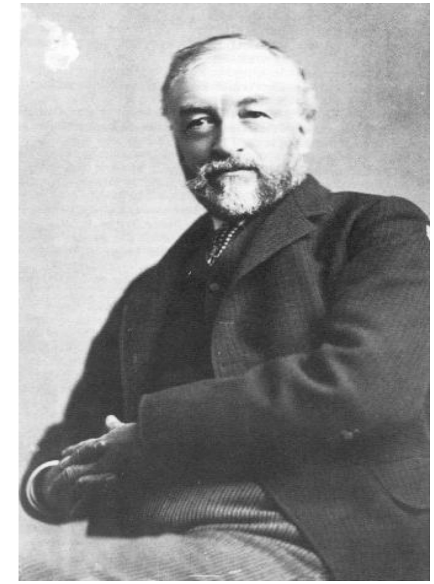
Same deduction, using the Stefan Boltzmann law

Deduced by C. Pouillet, using the Dulong–Petit law

[Dufresne, 2008]

Measurement of the infrared spectra

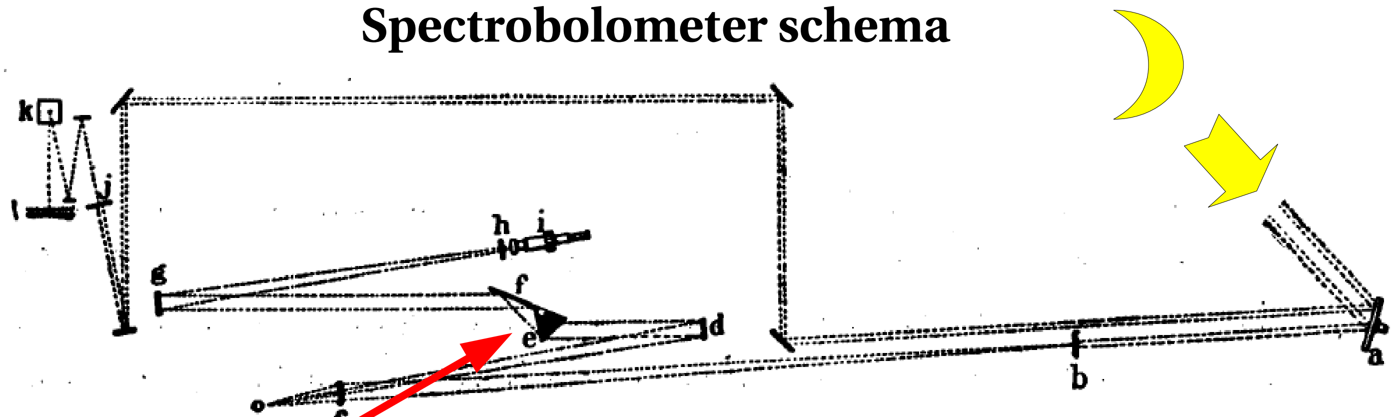
- Developed the spectrobolometer
- Measured the solar spectra
- Measured the infrared radiation coming from the moon



Samuel Langley

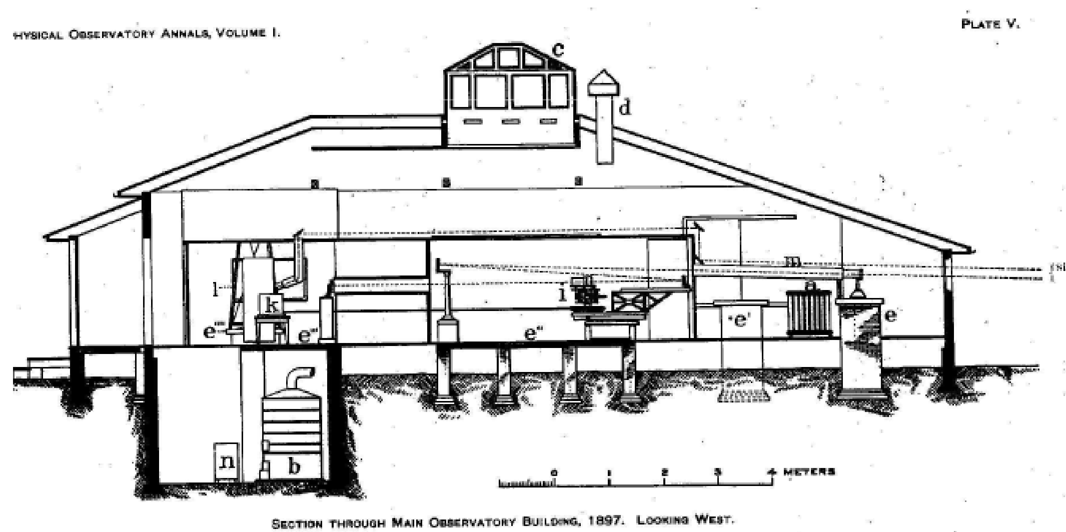
(1834-1906)

Spectrobolometer schema



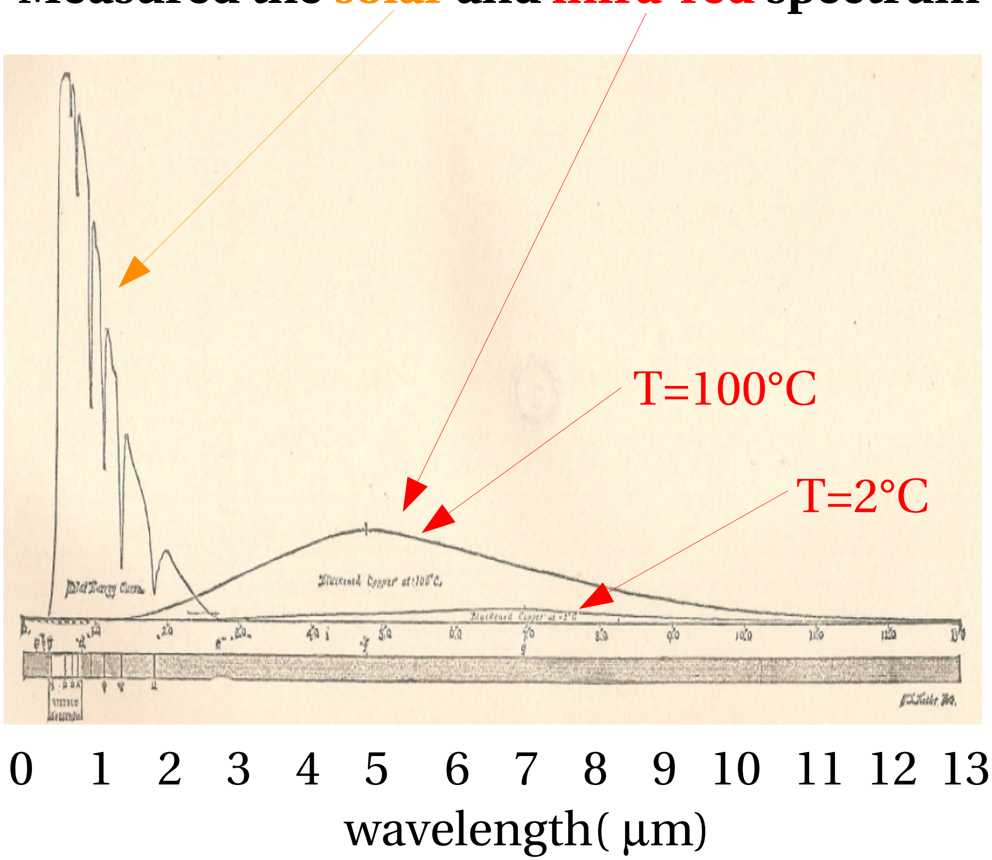
Rock salt prism (NaCl)

Going from deviation angles to wavelength require refractive index values, which were not known

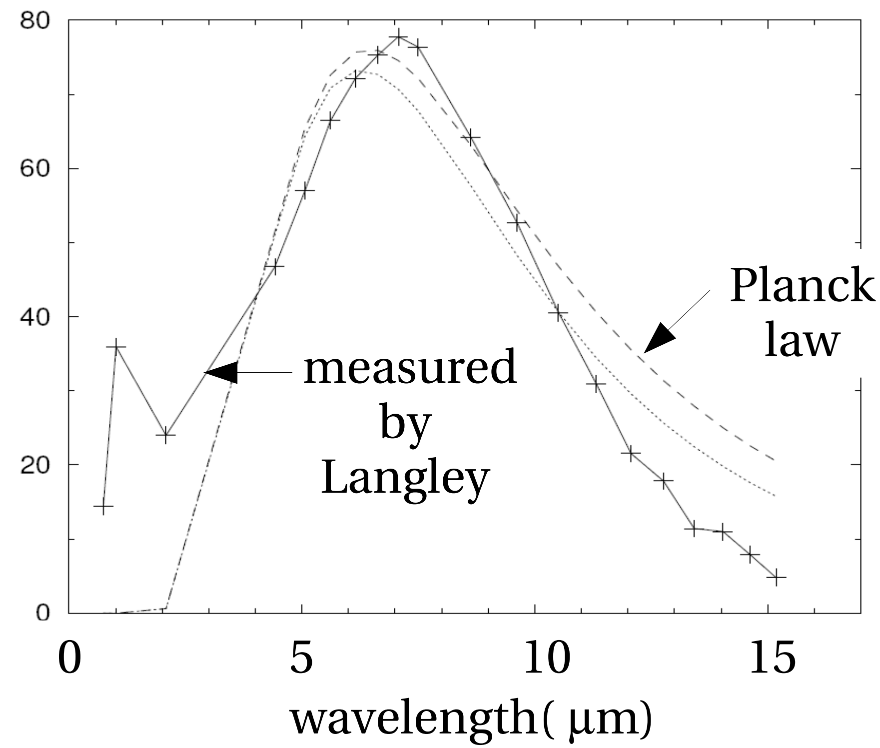


Measurement of the infrared spectra

Measured the solar and infra-red spectrum



Measured infra-red spectra, T=178°C



Current refractive index values are used to convert deviation angle to wavelength

- **He observed, for the first time, the spectral separation between solar radiation and earth thermal radiation**
- He was not satisfied by its measured of the infrared radiation coming from the moon
- (He overestimated by a factor o 2 the solar constant)

Estimate of the green house effect

On the Influence of Carbonic Acid in the Air upon the Temperature of the Ground, S. Arrhenius,1896.

- Extended previous works done by Fourier, Pouillet, Tyndall et Langley
- Used Langley observations to estimate the infrared absorption of the atmosphere (CO_2, H_2O)
- Developed the single layer greenhouse model and computed the green house effect on Earth
- CO_2 may be the cause of past climate change and may change climate in the future

Svante Arrhenius
(1859-1927)

- **He estimated that a doubling of CO_2 => $\Delta T \approx$ 4 to 5°C**
- These values are close to current estimate (2-4°C)
- **Are the results obtained by Arrhenius robust** *[Ramanathan &Vogelmann, 1997]* **or fortuitous?**

Estimate of the green house effect

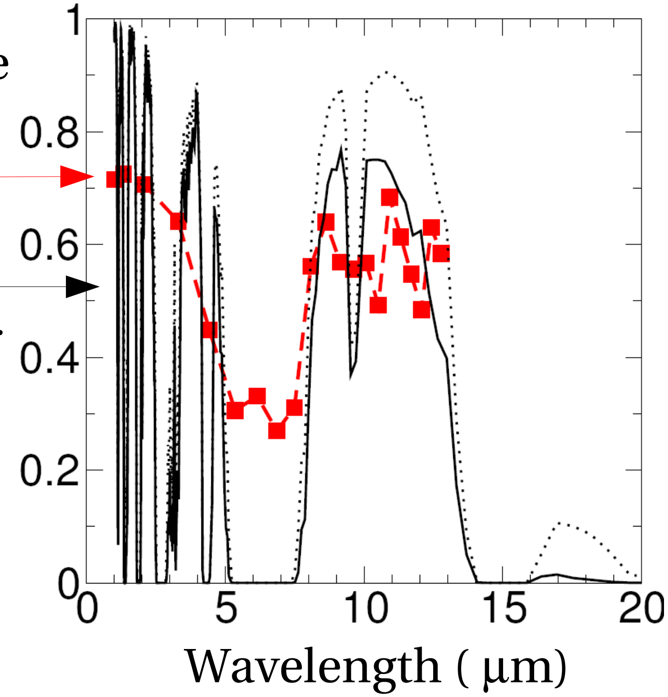
Infrared atmospheric transmitivity

CO_2+H_20

For a « standard » atmosphere

using Arrhenius data

current estimate, with a radiative model, for two water vapor contents (15 et 30 kg.m^{-2})



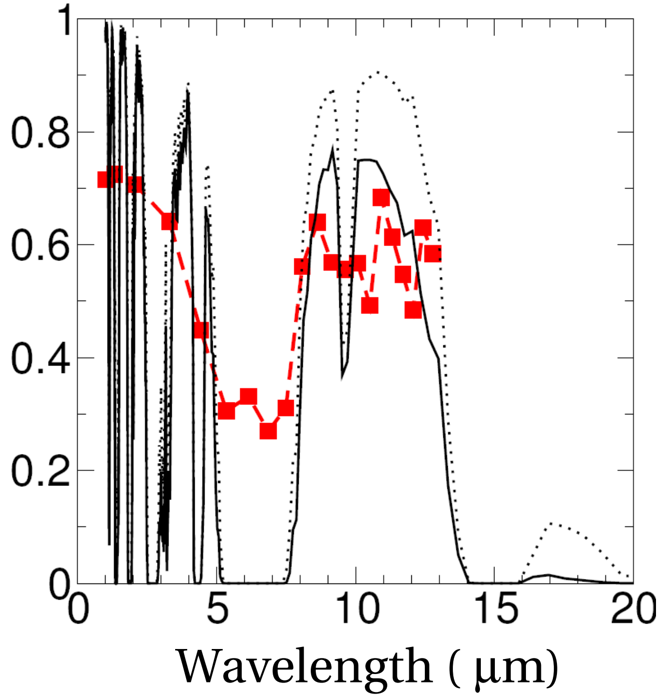
To separate the individual CO_2 and H_2O contributions, Arrhenius

- computed correlations between observed atmospheric transmitivity and humidity near surface
- made ad-hoc corrections on the observed atmospheric transmitivity

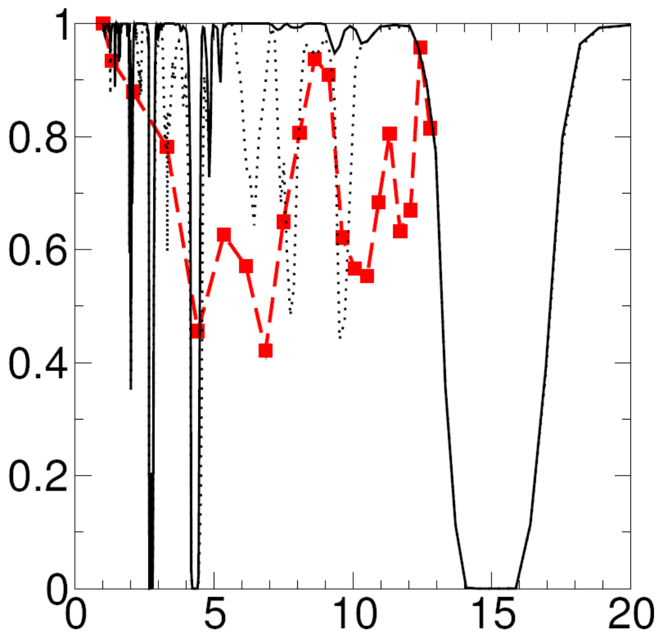
Estimate of the green house effect

Infrared atmospheric transmitivity

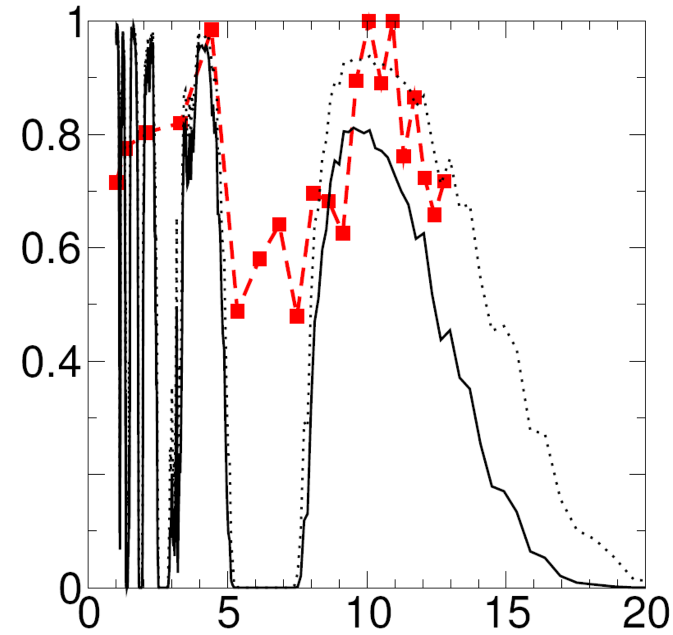
CO_2+H_20



CO_2



H_2O

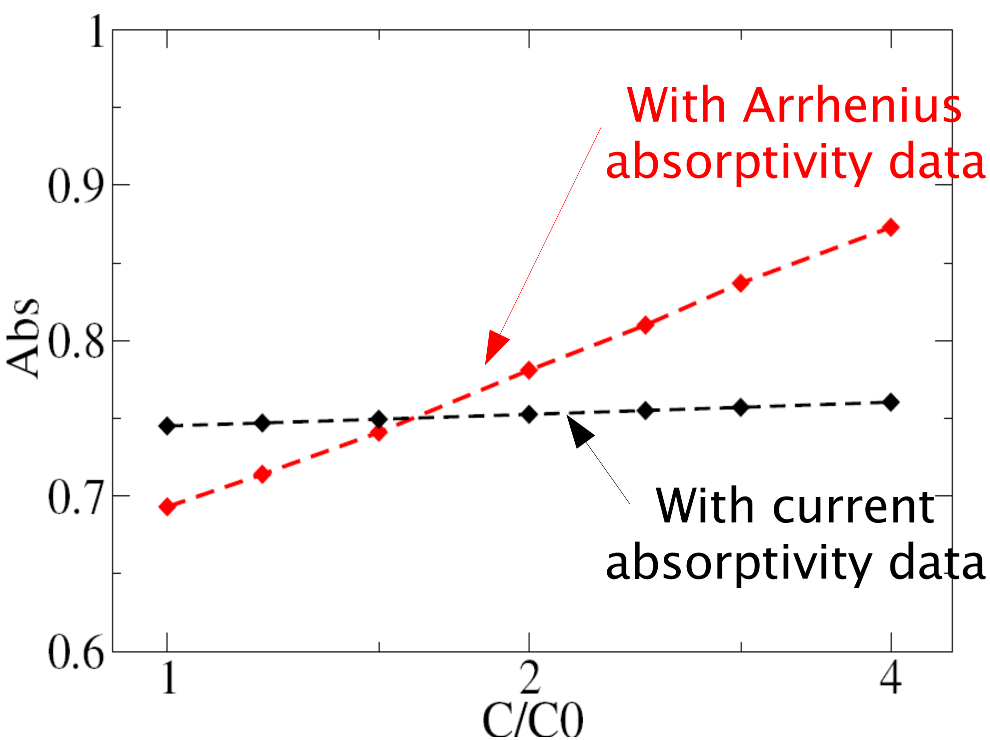


- ***Observations do not include the 15 μm absorption band of CO_2***
- The individual CO_2 and H_2O contributions are not well separate

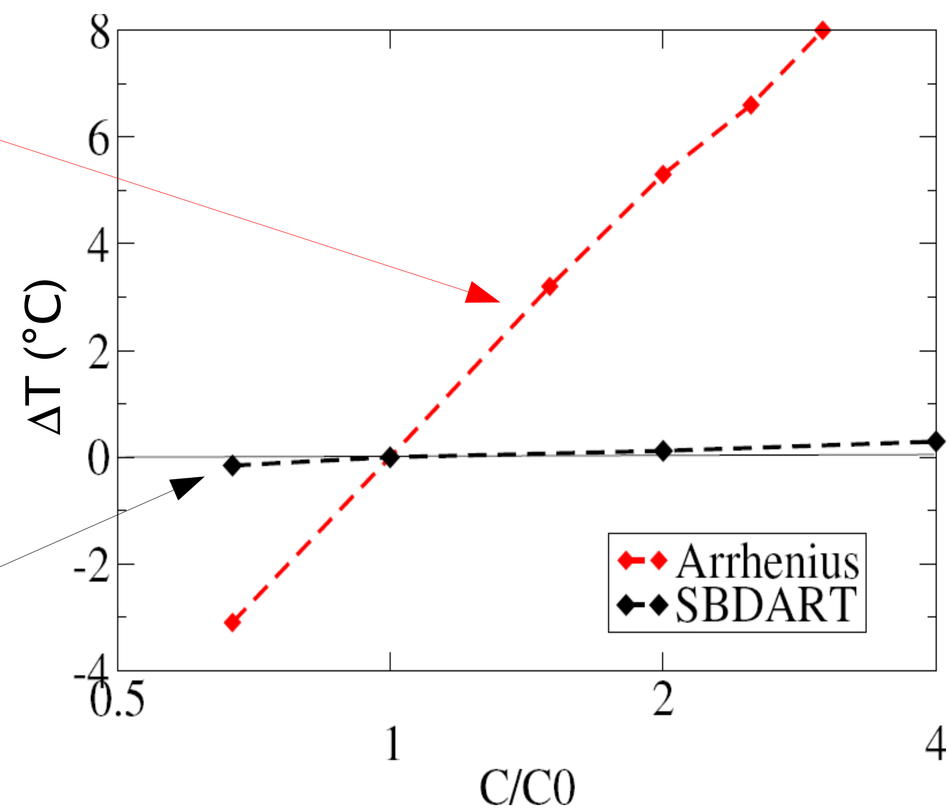
Estimate of the green house effect

Sensitivity to a change of the CO_2 concentration

Mean infrared absorptivity of the atmosphere as a function of the relative CO_2 concentration C/C0



Temperature change ΔT (°C) as a function of the relative CO_2 concentration C/C0 **for a single layer greenhouse model**



Estimate of the green house effect by Svante Arrhenius

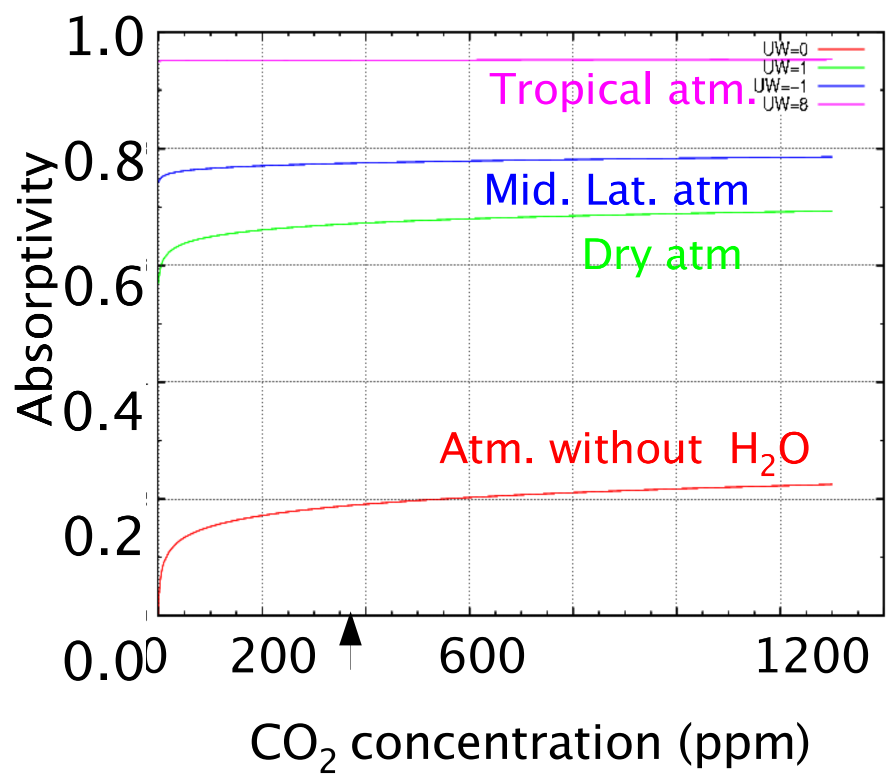
Absorptivity of the atmosphere:

- Spectral measurements do not cover the 15 µm CO_2 band
- The CO_2 absorptivity estimate is strongly contaminated by H_2O

Single layer greenhouse model:

- Do not include the vertical temperature gradient of the atmosphere
- Is not valid for greenhouse gases, like CO_2, for which the absorption is **saturated**

The increase of temperature for a doubling of CO_2 concentration obtained by Arrhenius ($\Delta T \approx 4°C$) is closed to current estimate ($\Delta T \approx 2\text{–}4°C$), **but this result is fortuitous.**

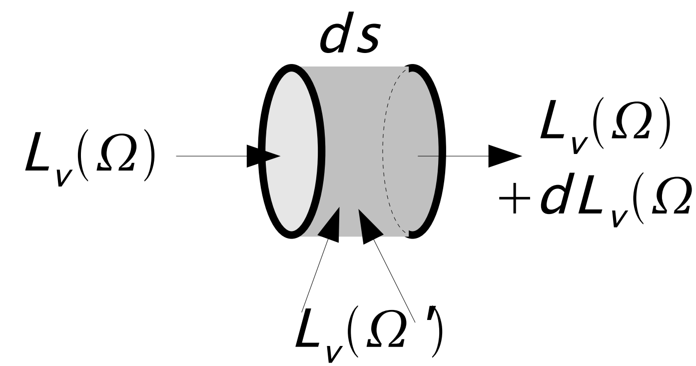


Analysis of the greenhouse effect on Earth using the Net Exchange Formulation

The increase of the green house gas concentration decreases the cooling of the surface:

- But what happens within the atmosphere?
- Is the atmosphere cooled or heated?
- It is the same for H_2O and CO_2 ?

Net Exchange Formulation (NEF)



Flux formulation:

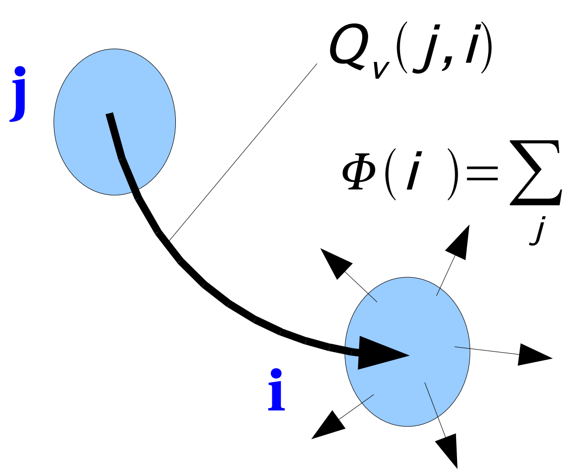
1- radiative transfer equation

$$\frac{dL_\nu(\Omega)}{ds} = -\kappa_\nu L_\nu(\Omega) + \kappa_\nu B_\nu(T) - \sigma_\nu L_\nu(\Omega) + \sigma_\nu \frac{1}{4\pi} \int_{4\pi} P(\Omega', \Omega) L_\nu(\Omega') d\Omega'$$

2- computation of the radiances and radiative flux

3- the heat budget Φ_ν is the divergence of the radiative flux

Exchange Formulation:

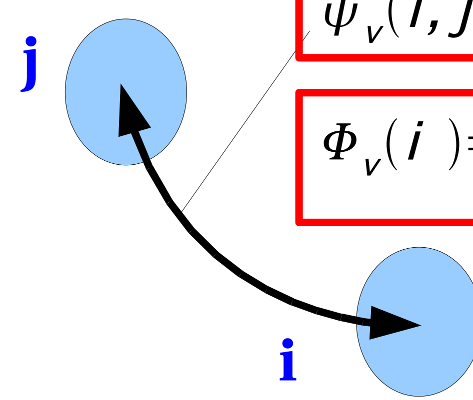


$$\Phi(i) = \sum_j Q_\nu(j,i) - E_\nu(i)$$

Net Exchange Formulation (NEF)

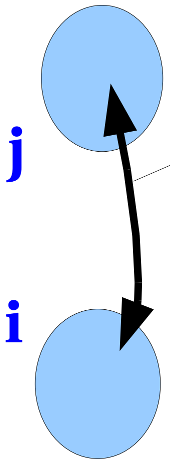
$$\boxed{\psi_\nu(i,j) = Q_\nu(i,j) - Q_\nu(j,i)}$$

$$\boxed{\Phi_\nu(i) = \sum_j \psi_\nu(i,j)}$$



[Green, 1967]

Net Exchange Formulation (NEF)



$$\boxed{\psi_\nu(i,j)=Q_\nu(i,j)-Q_\nu(j,i)}$$

$$\boxed{\Phi_\nu(i)=\sum_j \psi_\nu(i,j)}$$

Net Exchange between i and j = difference between radiation
emitted by i and absorbed by j
– emitted by j and absorbed by i

$$\psi_\nu(i,j)=\int_\Gamma \underbrace{(B_\nu(y_\gamma)-B_\nu(x_\gamma))}_{\text{Planck function}}\,\underbrace{O_\nu(x_\gamma,y_\gamma)}_{\text{Optical exchange factor}}\,d\gamma$$

Planck function Optical exchange factor

- If the two extremities are « surfaces » (i.e. black or grey bodies, the surface or space)

$$O_\nu(x_\gamma,y_\gamma)=\tau_{\nu,\gamma}$$

with τ transitivity

- If one extremity is a volume and the other is a « surface » (e.g. cooling to space)

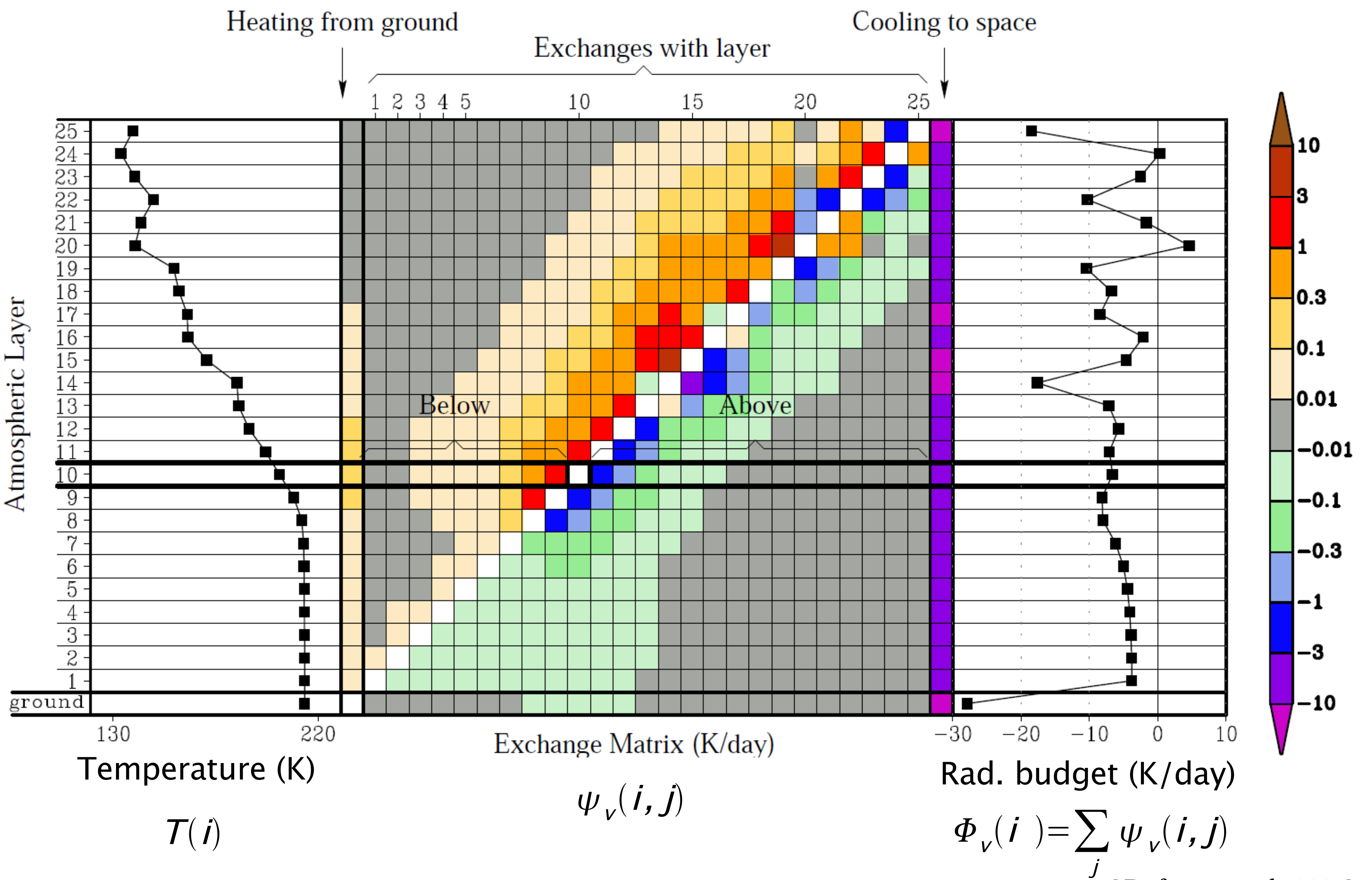
$$O_\nu(x_\gamma,y_\gamma)=\left|\frac{\partial \tau_{\nu,\gamma}}{\partial x_\gamma}\right|$$

- If the two extremities are volume

$$O_\nu(x_\gamma,y_\gamma)=\left|\frac{\partial^2 \tau_{\nu,\gamma}}{\partial x_\gamma \partial y_\gamma}\right|$$

[Dufresne et al., 2005]

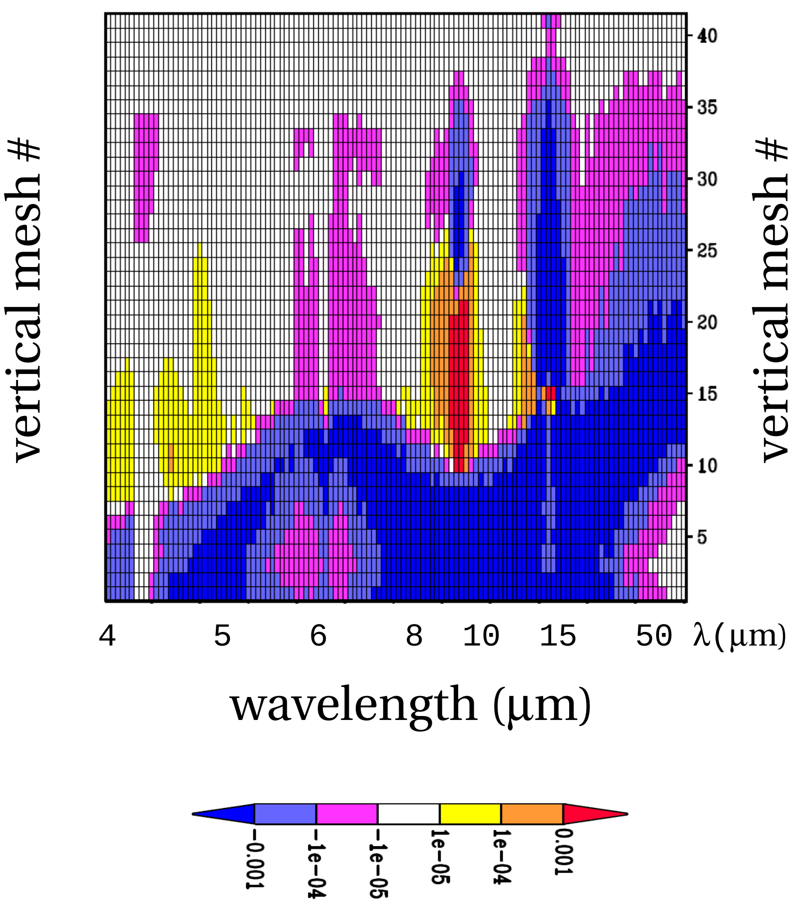
NEF analysis of the Mars atmosphere



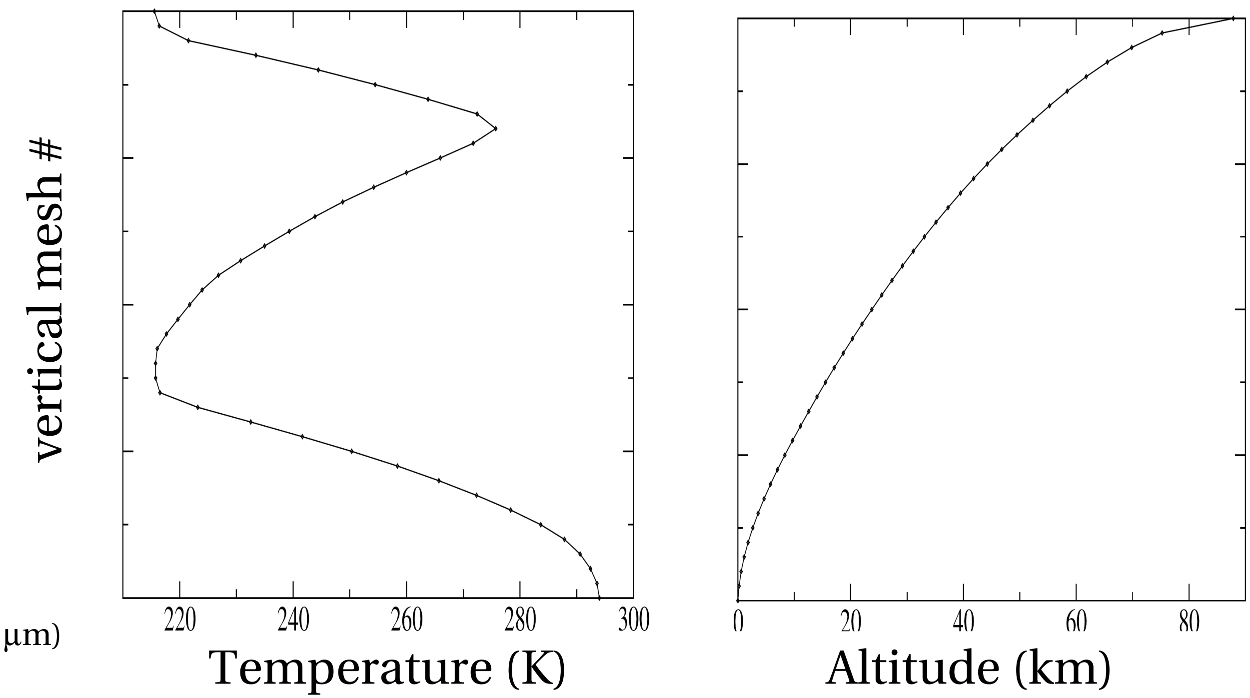
[Dufresne et al., 2005]

NEF analysis of the radiative exchanges for the Earth atmosphere

Spectral dependence of the **radiative budget** in the atmosphere



Mid latitude summer atmospheric profile
(MLS, RTMIP case, Collins et al. 2006)



[Eymet et al., 2004]

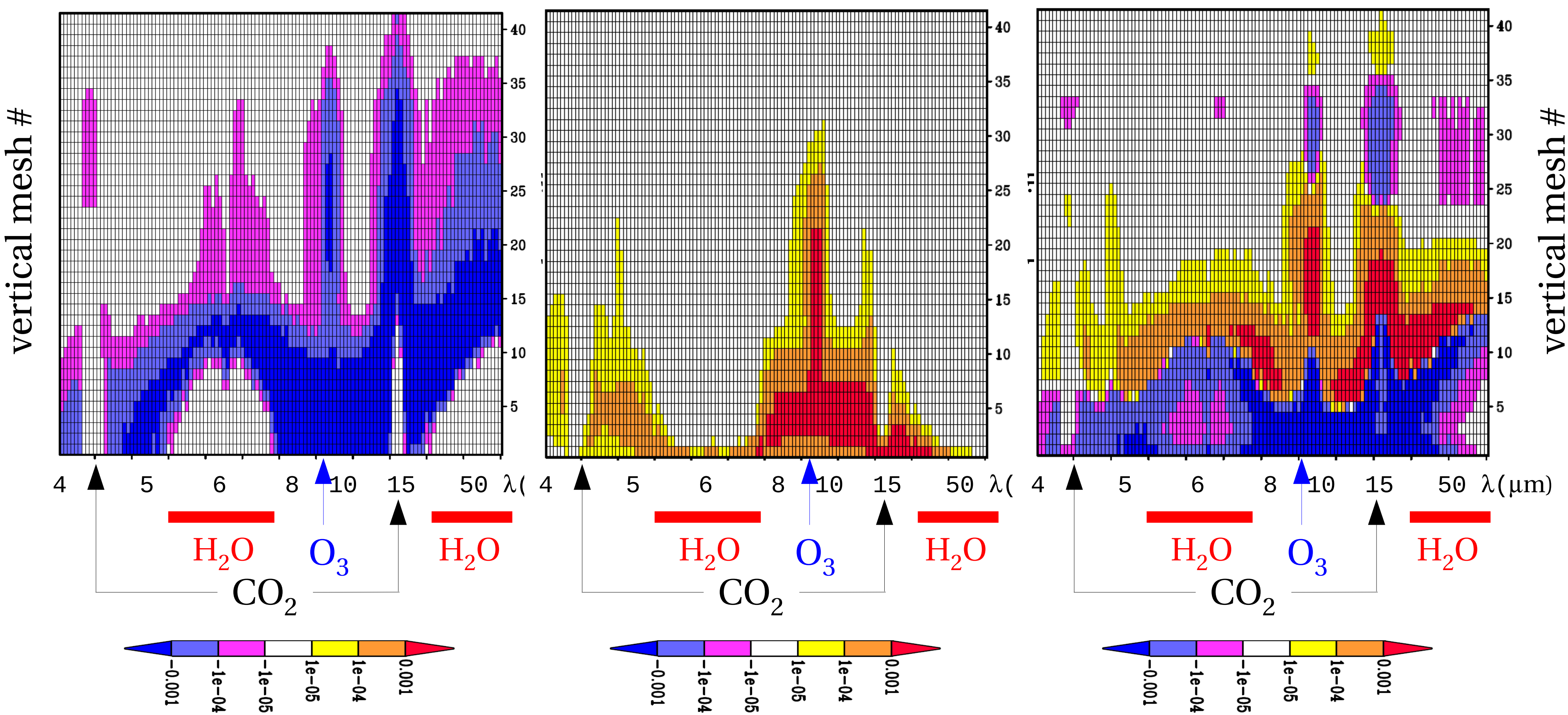
NEF analysis of the radiative exchanges

Radiative budget of layer i → $\Phi_i = \Psi_{i,e} + \Psi_{i,s} + \Psi_{i,a}$

Exchange with space

Exchange with the surface

Exchange with the rest of the atmosphere



Focus on the exchanges with space

Net exchange between an elementary volume x of mass dm and the space s :

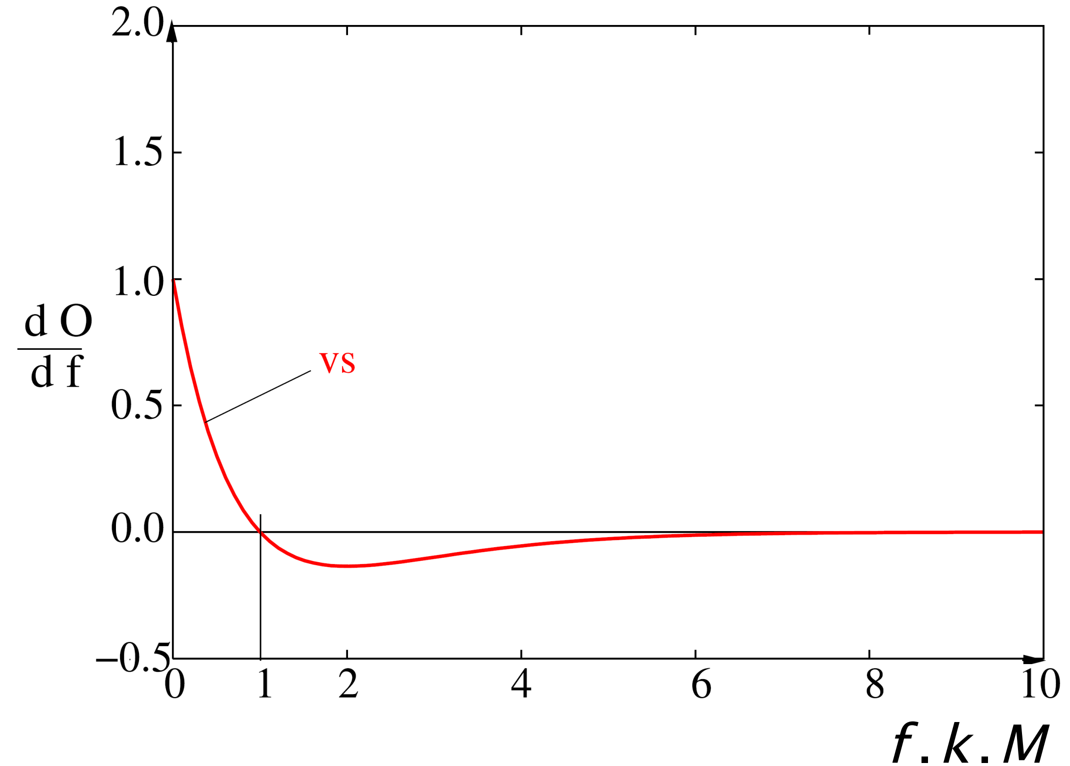
$$\psi_\nu(x,s) = -B_\nu(T_x)\, O_\nu(x,s)\, dm$$

Optical exchange factor:

$$O_\nu(x,s) = \left|\frac{\partial \tau_\nu}{\partial m}\right| = f.k.\exp(-f.k.M)$$

with:
- f : mass fraction of the absorbing gas
- k: absorption coefficient
- M: gas mass above volume x

Sensitivity of the optical exchange factor to the fraction of the absorbing gas, **as a function of the optical thickness** between x and the space.



The optical exchange factor increases with an increase of the fraction of the absorbing gas when the optical thickness with space is below 1, otherwise it decreases

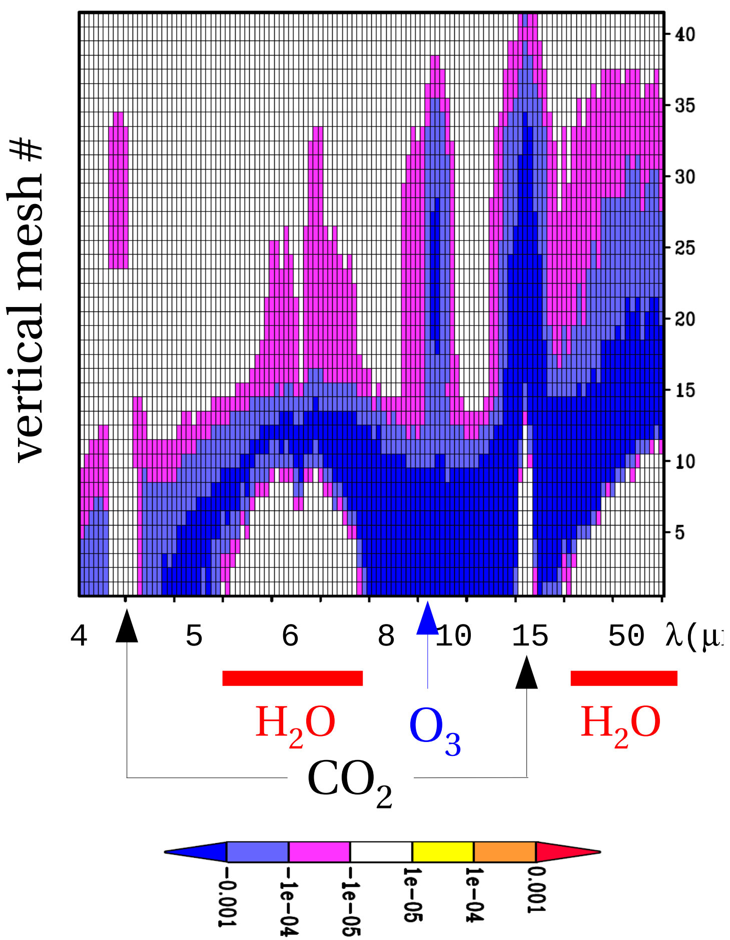
Focus on the exchanges with space

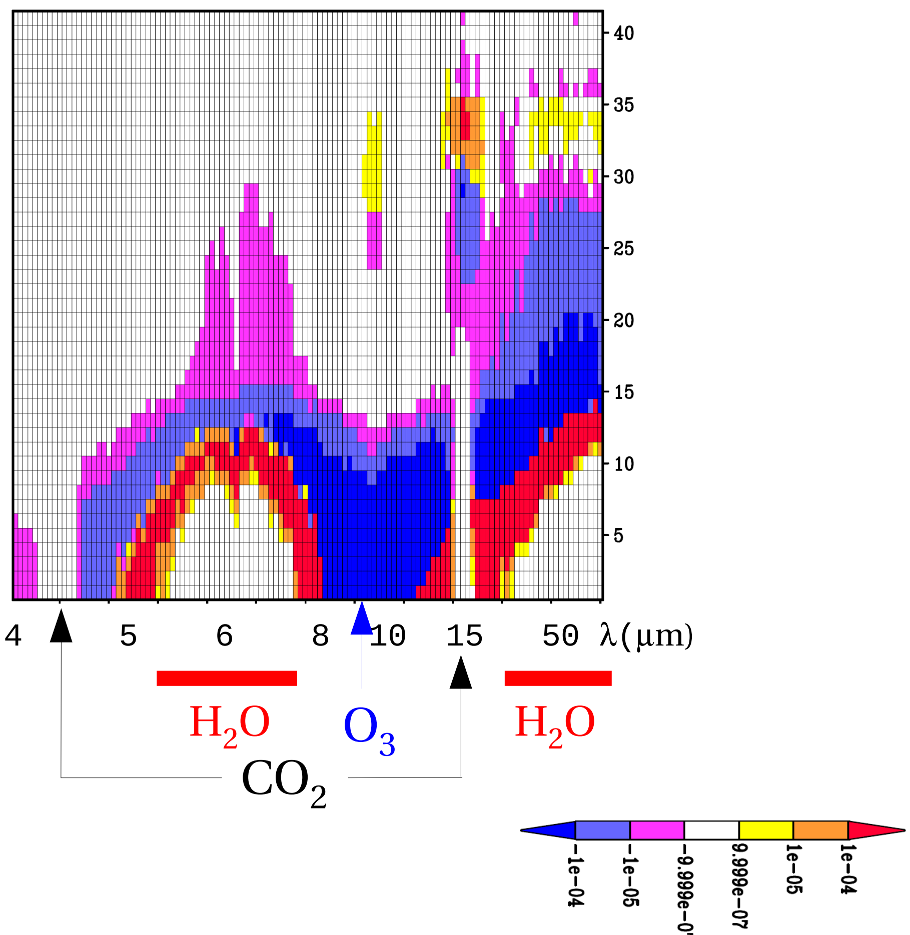
Exchanges with space

Standard atmosphere

Change of the exchanges with space

$H_20 + 20\%$





[V. Eymet, Laplace]

Focus on the exchanges with space

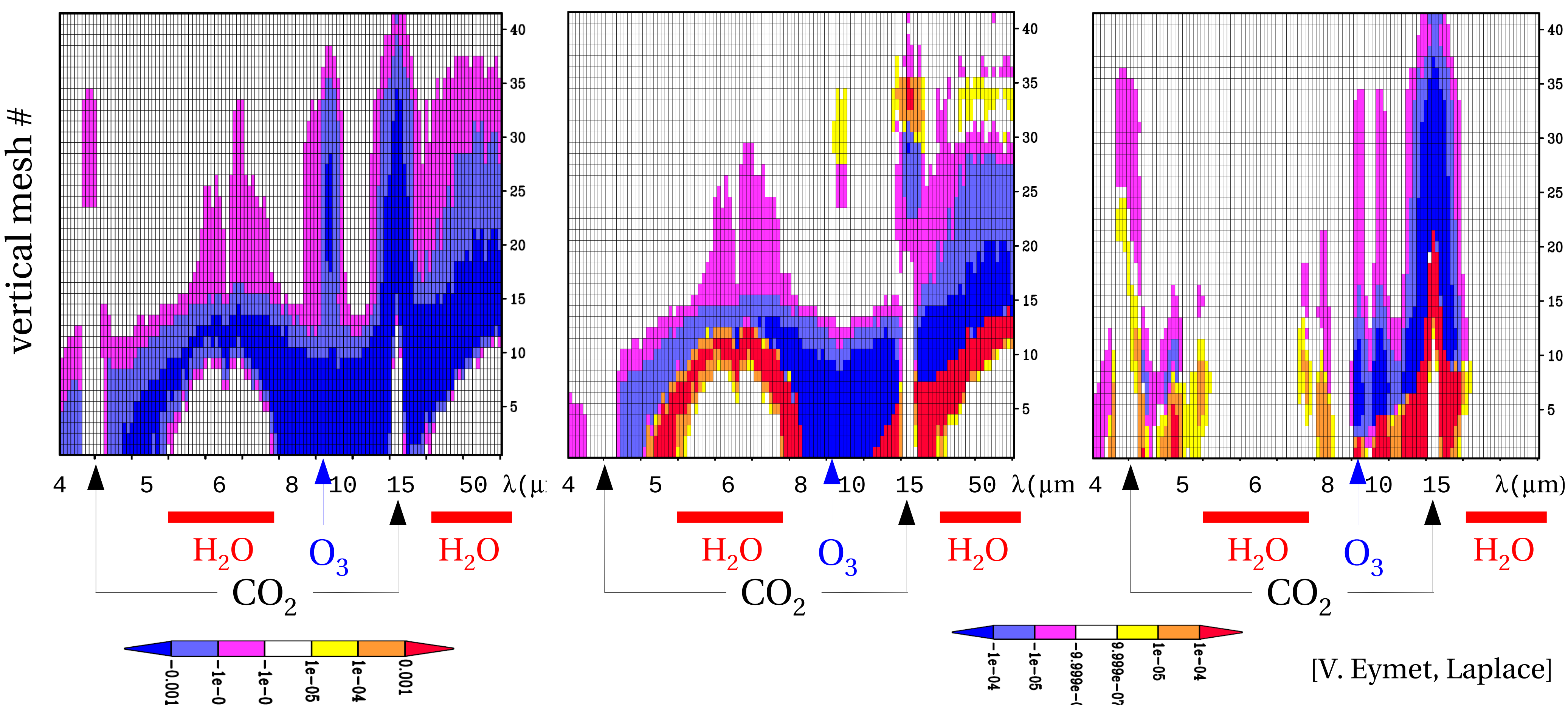
Exchanges with space

Standard atmosphere

Change of the exchanges with space

H_20 + 20%

CO_2 x 2



[V. Eymet, Laplace]

Focus on the exchanges within the atmosphere

Net exchange between two elementary volumes *x and y* of mass dm_x and dm_y:

$$\psi_\nu(x,y)=(B_\nu(T_y)-B_\nu(T_x))\,O_\nu(x,y)\,dm_x\,dm_y$$

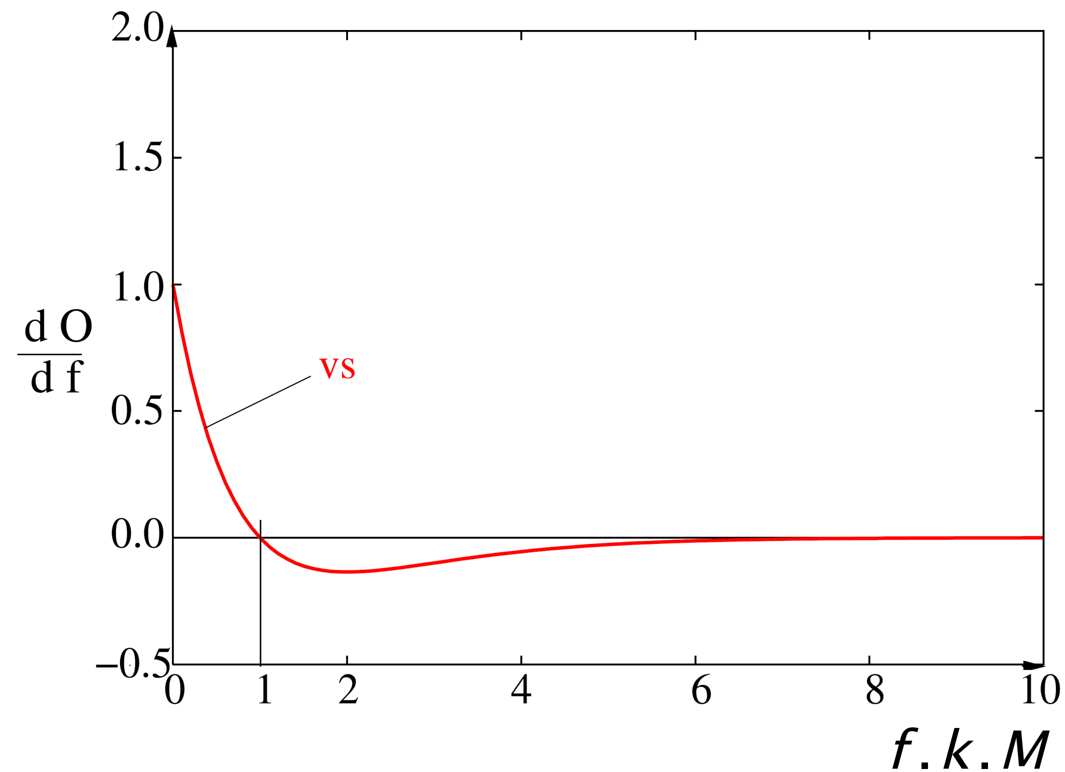
Optical exchange factor:

$$O_\nu(x,y)=\left|\frac{\partial \tau_\nu}{\partial m_x \partial m_y}\right|=f^2.k^2.\exp(-f.k.M)$$

with:

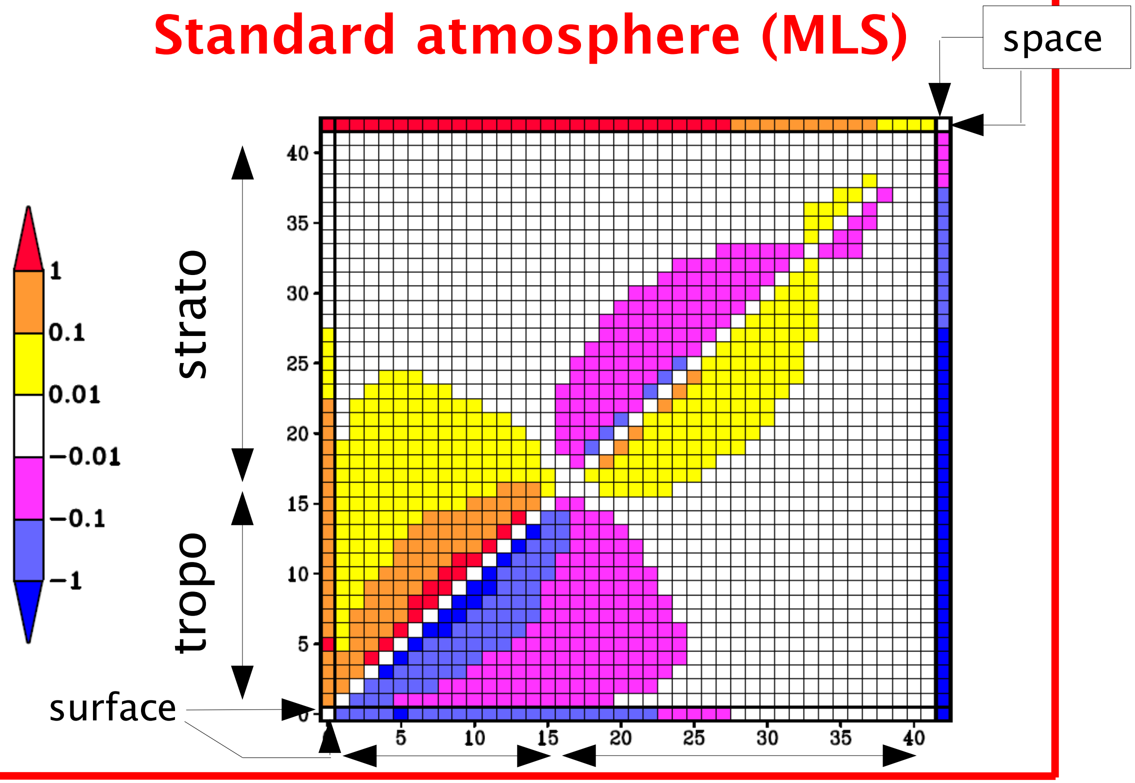
- f: mass fraction of the absorbing gas
- k: absorption coefficient
- M: gas mass above volume x

Sensitivity of the optical exchange factor to the fraction of the absorbing gas, **as a function of the optical thickness** between *x* and y



The optical exchange factor increases with an increase of the fraction of the absorbing gas when the optical thickness between x and y is below 2, otherwise it decreases

Standard atmosphere (MLS)

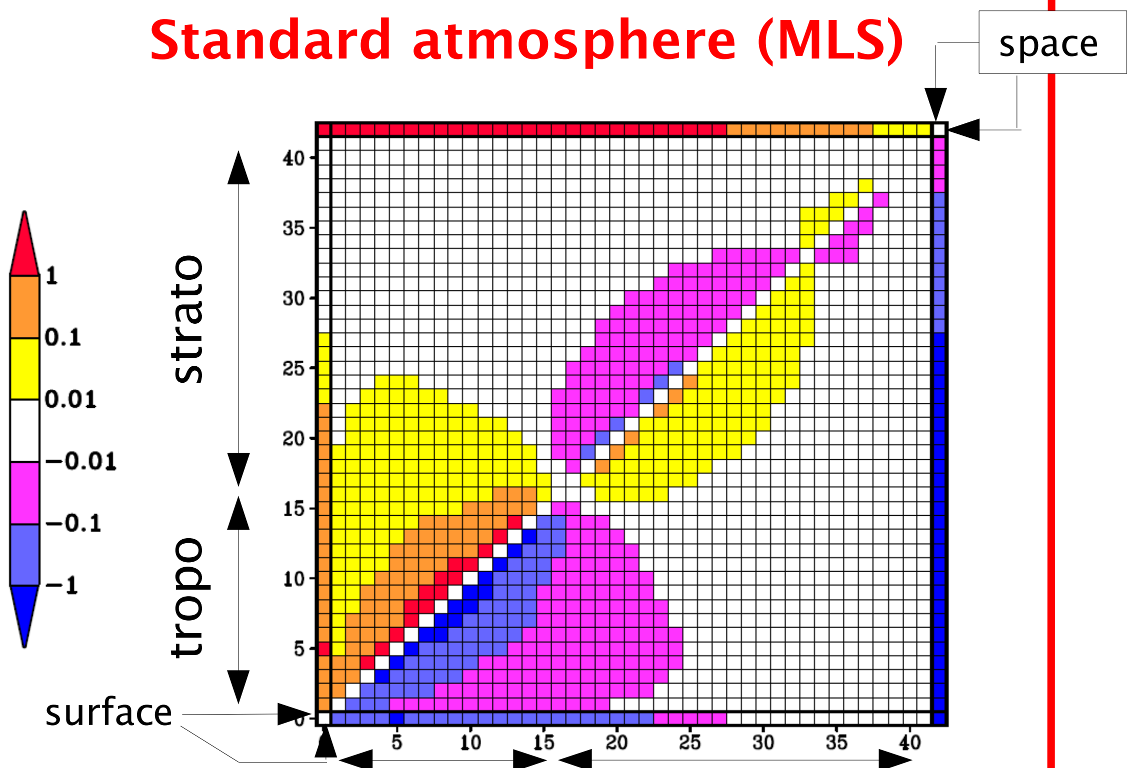


Radiative net exchange matrix (W.m^{-2})

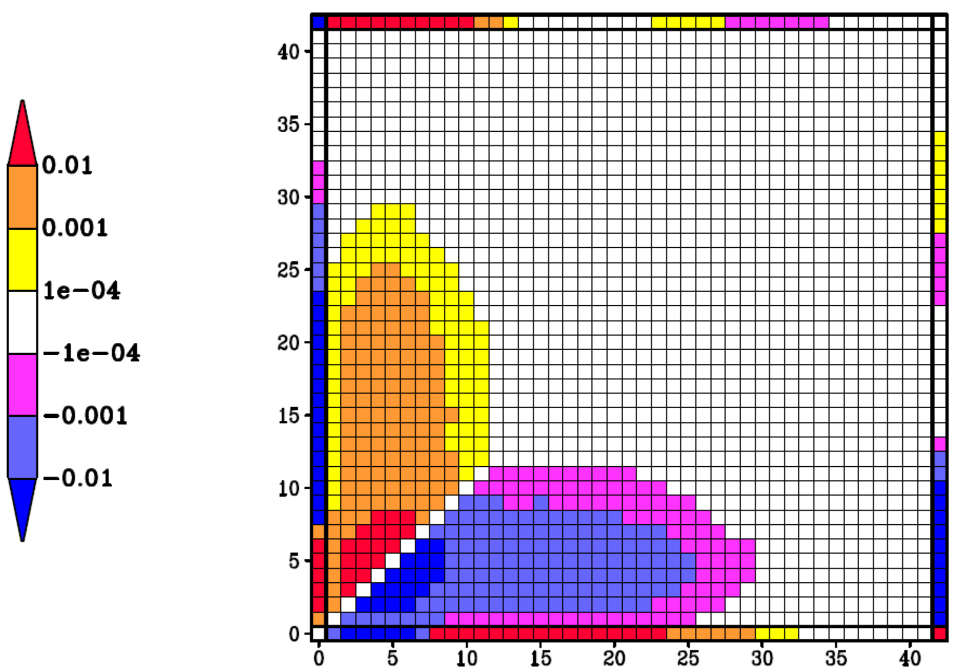
Standard atmosphere (MLS)

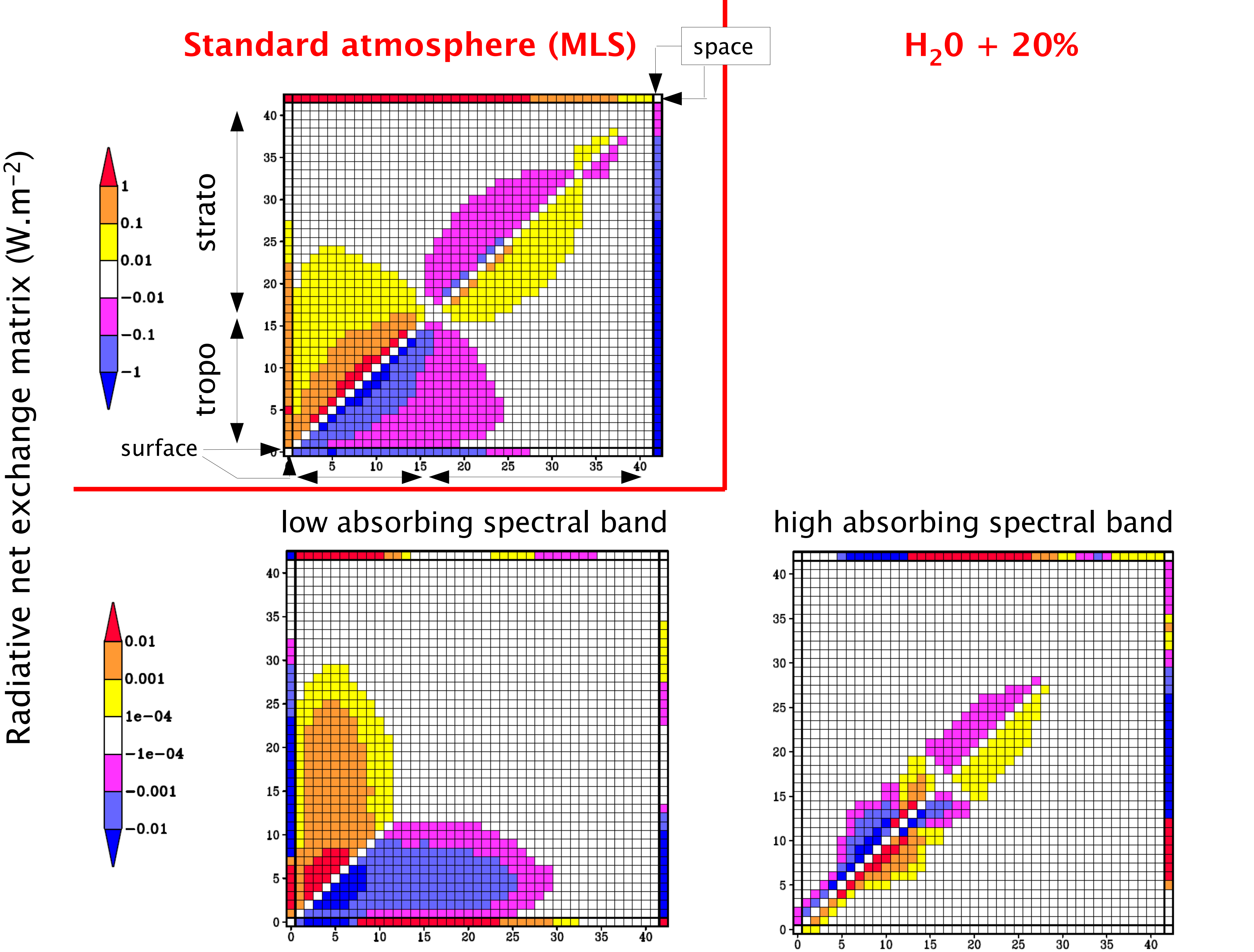
H_2O + 20%

Radiative net exchange matrix ($W.m^{-2}$)

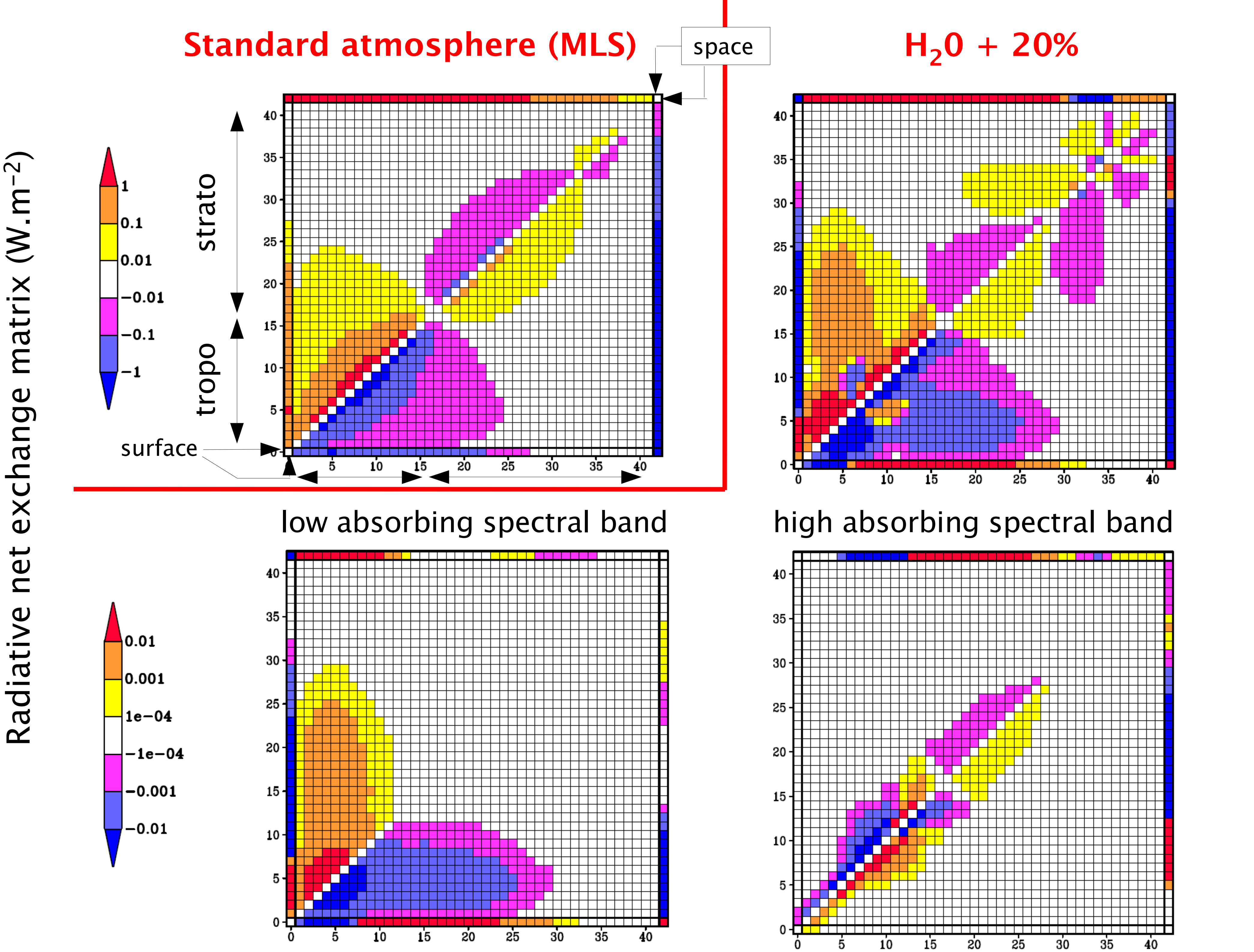


low absorbing spectral band





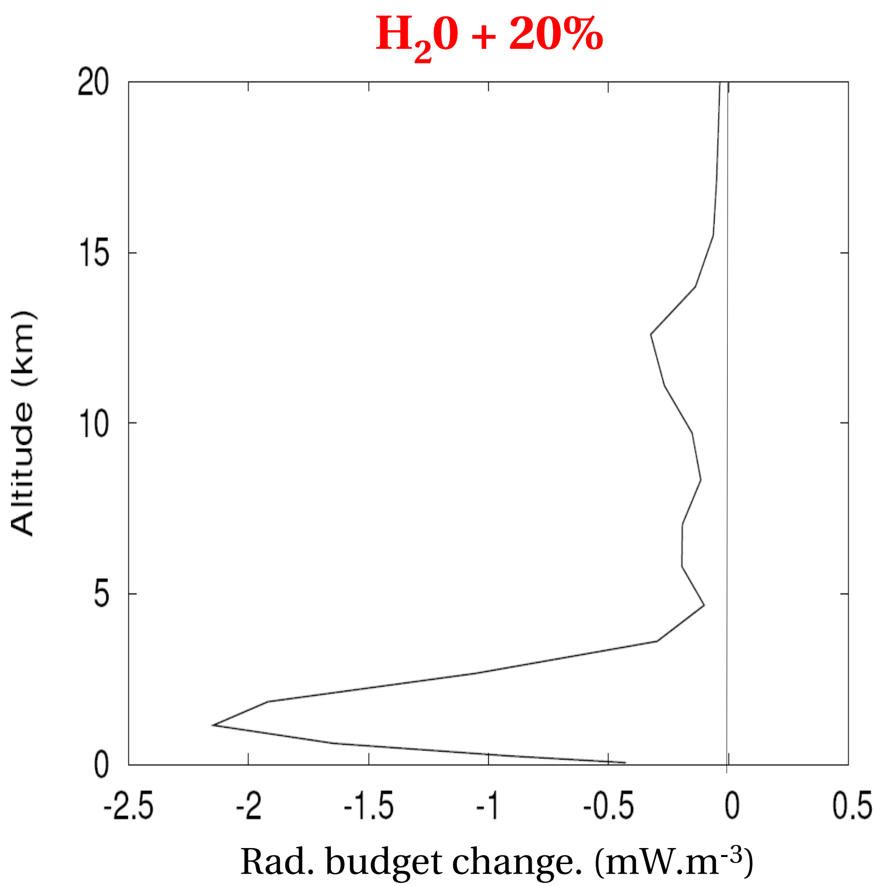
Standard atmosphere (MLS)
H20 + 20%
space
surface
strato
tropo
Radiative net exchange matrix (W.m-2)
1
0.1
0.01
−0.01
−0.1
−1
low absorbing spectral band
high absorbing spectral band
0.01
0.001
1e−04
−1e−04
−0.001
−0.01

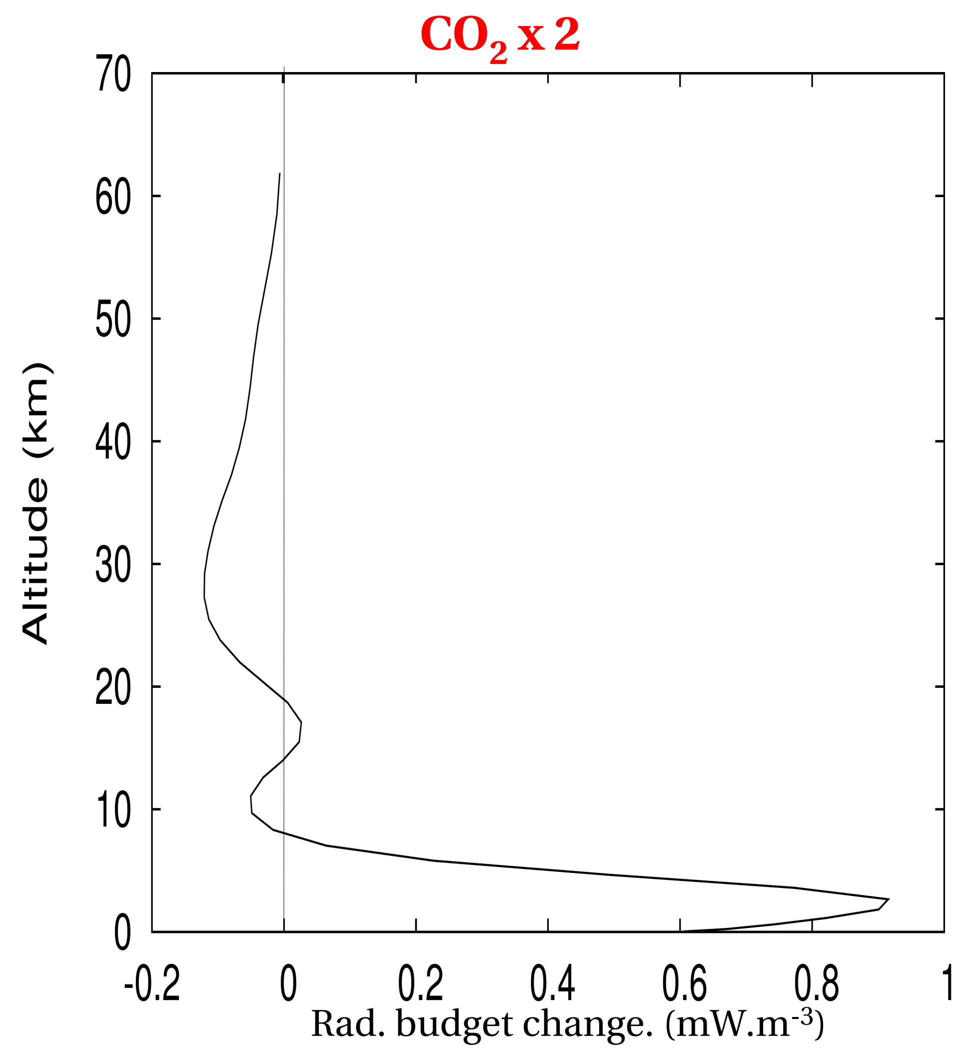


Standard atmosphere (MLS)
space
H_20 + 20%
Radiative net exchange matrix (W.m^{-2})
strato
tropo
surface
1
0.1
0.01
−0.01
−0.1
−1
low absorbing spectral band
high absorbing spectral band
0.01
0.001
1e−04
−1e−04
−0.001
−0.01

Analysis of the greenhouse effect on Earth

Radiative budget changes





Surface:	+ 12,1 $W.m^{-2}$	Surface:	+ 1,5 $W.m^{-2}$
Atmosphere:	**- 8,1 $W.m^{-2}$**	**Atmosphere:**	**+ 1,3 $W.m^{-2}$**
Space:	- 4,0 $W.m^{-2}$	Space:	- 2,8 $W.m^{-2}$

In summary

Arrhenius estimate of CO_2 impact on the surface temperature is erroneous for two majors reasons (that partly compensate)

- Wrong absorptivity values of CO_2 and H_2O
- Inadequacy of the single layer greenhouse model to saturated green house gases, like CO_2

The consistency of Arrhenius results with current estimates appear to be fortuitous.

The Net Exchange Formalism is a powerful tool to analyse radiative exchanges.

An increase of the green house gas concentration

- decreases the cooling of the surface
- cools or heats the atmosphere, depending on the radiative properties of the gas. On average:
  - for H_2O: increase of the cooling of the atmosphere
  - for CO_2: decrease of the cooling of the atmosphere


Thank you for your attention